# Comparison of the WSA-ENLIL model with three cone types

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**Abstract.** We have made a comparison of the WSA-ENLIL model with three cone types using 29 halo CMEs from 2001 to 2002. These halo CMEs have cone model parameters as well as their associated interplanetary (IP) shocks. For this study we consider three different cone types (an asymmetric cone model, an ice-cream cone model, and an elliptical cone model) to determine 3-D CME parameters (radial velocity, angular width, and source location), which are the input values of the WSA-ENLIL model. The mean absolute error (MAE) of the arrival times for the asymmetric cone model is 10.6 hours, which is about 1 hour smaller than those of the other models. The MAE of their ensemble average errors for three cone models is 9.5 hours. However, this value is still larger than that (8.8 hours) of the empirical model of Kim et al. (2007). We compare the predicted and observed peak values of solar wind parameters (speed and density) near the shock arrival time and find that these values are approximately similar to each other.

## 1. Introduction

Coronal mass ejections (CMEs) are one of solar eruptive phenomena propagated through the heliosphere. Especially halo coronal mass ejections (HCMEs) are likely to directly impact the Earth and change the condition of space environment. These HCMEs and their associated shocks can cause severe geomagnetic storms (Gosling et al., 1991). Therefore it is important to predict the propagation of a CME and its associated shocks at the Earth. Many efforts have been made to predict it using empirical (e.g. Gopalswamy et al., 2005; Kim et al., 2007) and scientific models (e.g. Arge et al., 2005; Odstrcil, 2003). Scientific models provide a global view of an interplanetary structure.

The empirical models use the initial speed of a CME observed by SOHO/LASCO to predict its arrival at the Earth. The empirical shock arrival (ESA) model is to predict the arrival time of a shock at 1 AU (Gopalswamy et al., 2005) by assuming a constant acceleration. Kim et al. (2007) found an empirical relationship between CME initial speed and shock travel time using 91 CME-associated IP shocks. These empirical models can predict the shock arrival in near real-time but they do not give a global view about a CME evolution in the interplanetary space.

The WSA-ENLIL cone model is one of the scientific models widely used for the CME propagation. This model has three components: (1) the Wang-Sheely-Arge (WSA) model; which calculates solar wind speed and magnetic field (Arge et al., 2004), (2) the ENLIL model; a time-dependent 3D MHD model (Odstrcil et al., 2004), and (3) a CME cone model.

The CME cone model developed by Zhao et al. (2002) assumes that a CME propagates radially and its shape is a cone with constant angular width. Xie et al. (2004) made an analytic method based on Zhao et al. (2002). Xue et al. (2006) developed an ice-cream cone model that assumes the structure of the CME is a symmetrical ice-cream cone. This model is applicable to both HCMEs and non HCMEs. Michalek (2006) presented an asymmetric cone model by assuming that the structure of a CME is a cone with elliptic cross section.

In order to evaluate the WSA-ENLIL cone model, Taktakishvili et al. (2011) and Falkenberg et al. (2011) estimated the mean absolute errors (MAE) of arrival times for HCMEs using the elliptical cone model (Xie et al. 2004). Taktakishvili et al. (2011) found 6.9 h for 14 events that produced geomagnetic storms stronger or equal to Kp=8. On the other hand, Falkenberg et al. (2011) obtained 14.8 h for 36 events that were identified as shocks at both the Earth and the Mars. No attempt has been made a comparison of the model using different cone models.

In this study we compare the arrival time error of the WSA-ENLIL cone model based on three cone types using 29 HCMEs that have their corresponding IP shocks among 69 events of Michalek et al. (2007). In addition, we compare the results (arrival time, speed, and density) of the model with ACE satellite observations.

## 2. Model and Data

### 2.1. WSA-ENLIL Cone model

The WSA-ENLIL cone model has three components: the Wang-Sheely-Arge (WSA) model, the ENLIL model, and a CME cone model. The WSA coronal model is an empirical and physics-based coronal model (Arge and Pizzo, 2000). As its input data, the WSA model uses a synoptic magnetogram of the Sun; for instance, Mount Wilson Observatory (MWO), National Solar Observatory (NSO), or Global Oscillation Network Group (GONG). This model consists of Potential Field Source Surface (PFSS) model and Schatten Current Sheet (SCS) model to calculate the coronal magnetic fields from solar surface and outer coronal boundary, i.e., 21.5 solar radii. At longer distances, magnetic fields are assumed to be radial. An empirical velocity relationship is used to input the solar wind speed at the outer coronal boundary.

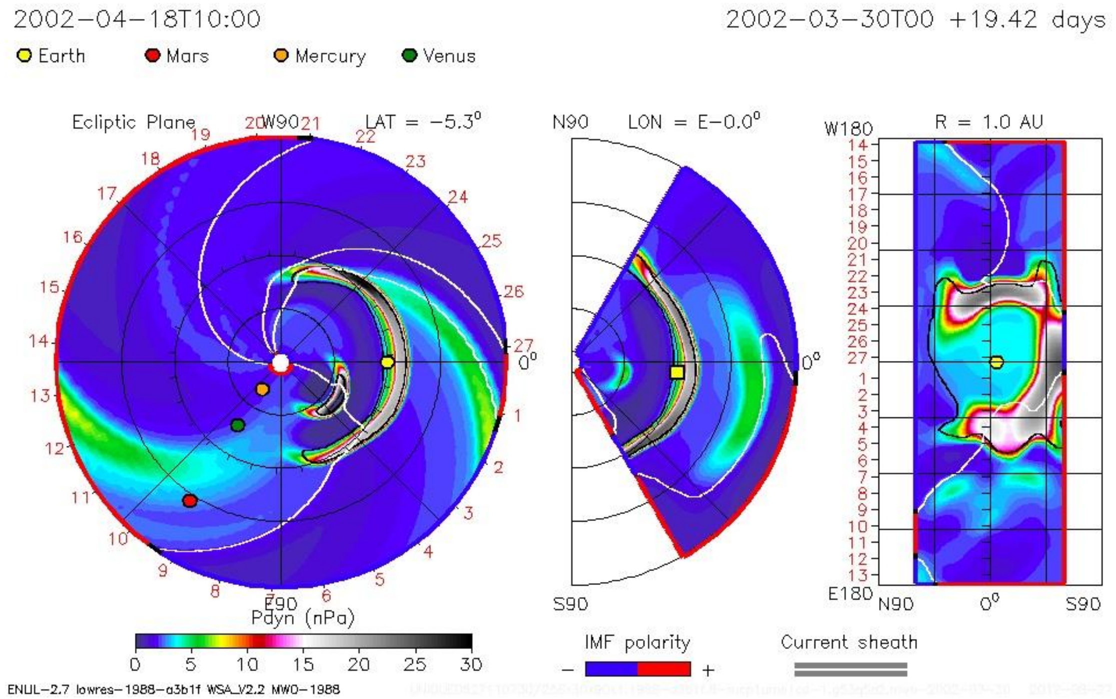


Figure 1. Snapshots of dynamic pressure for 15 and 17 April 2002 CMEs by the WSA-ENLIL Cone model with the asymmetric cone model.

The ENLIL model is a 3D MHD numerical model with two additional continuity equations used for the injected CME material and interplanetary magnetic fields polarity (Odistrcil and Pizzo, 1999a, 1999b). Its inner boundary is typically located at 21.5 solar radii. The ENLIL model can employ the WSA model for boundary condition. The ENLIL model calculates solar wind velocity, density, temperature, and magnetic field strength to simulate solar wind flow. To run the model for a CME, we need its parameters such as source location, angular width, radial velocity, and the time when it passes through the outer coronal boundary. Thus it uses a cone model to obtain the CME parameters.

2.2 CME cone model

The elliptical cone model (Xie et al., 2004, Figure 3a) is an analytic method developed by Zhao et al. (2002). This model assumes that the shape of a HCME is symmetrical circular and the projection of the cone is an ellipse.

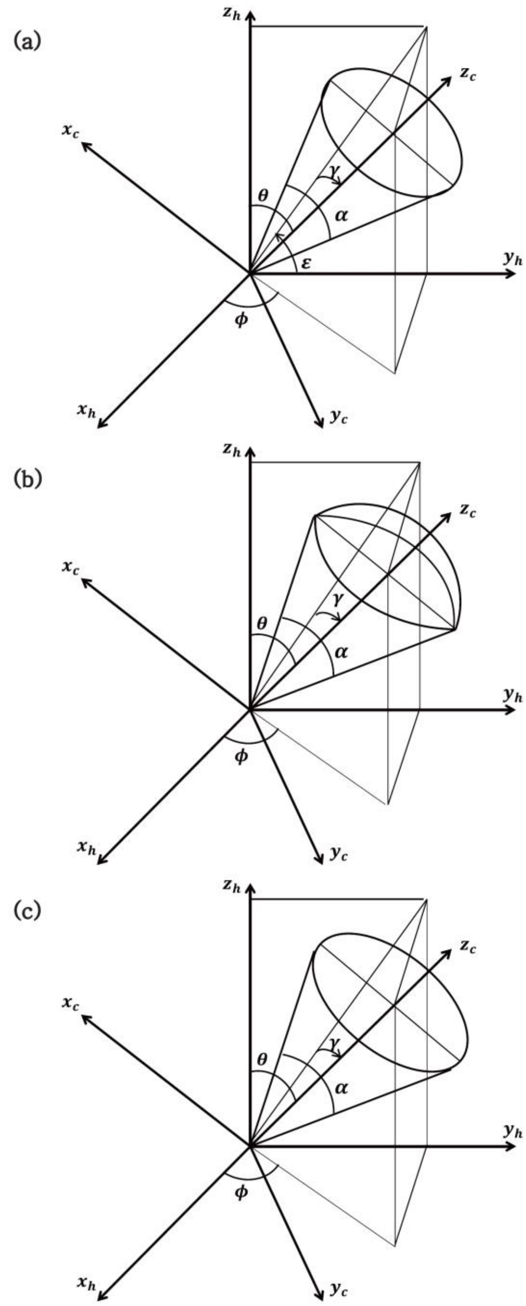


Figure 2. The structures of the cone models: (a) the elliptical cone model, (b) the ice-cream cone model, and (c) the asymmetric cone model

The ice-cream cone model (Xue et al., 2005, Figure 3b) assumes that the shape of a CME is a symmetrical cone with a sphere like an ice-cream. There are three steps to determine cone parameters. First, the possible source location of a CME is restricted near the flare location or an active region. Second, the projection speeds measured at different position angles are determined using the linear fitting method between height and time. Finally, we obtain the cone parameters using the least-square fitting method between measured and estimated projection speeds.

The asymmetric cone model (Michalek, 2006, Figure 3c) considers that the shape of a CME is an asymmetric cone and its cross section is an ellipse. A method to calculate the cone parameters is similar to that of the ice-cream cone model. There are two differences: (1) using the root mean square error (RMS error) instead of the least-square fitting method and (2) having angular widths at different position angles.

### 2.3. Data

In this study, we use 29 HCMEs in the SOHO/LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list) from 2001 to 2002. These HCMEs have cone model parameters such as radial velocity, angular width, and source location. Their associated shocks were identified by Gopalswamy et al. (2010). We use the Mount Wilson Observatory (MWO) magnetograms as an input of the WSA-ENLIL cone model. We use CME parameters from Michalek et al. (2007) for the asymmetric cone model. We directly determine the elliptical and the ice-cream cone model parameters (Na et al., 2013), while other input parameters are chosen as default values. To compare the results of the WSA-ENLIL model with observations, we use solar wind velocity and density data by the ACE, which are taken from Coordinated Data Analysis Web (CDAWeb) available at NASA's Goddard Space Flight Center (http://cdaweb.gsfc.nasa.gov/cdaweb/). We use the WSA-ENLIL cone model 2.7 versions and "Request A Run" by the Community Coordinated Modeling Center (CCMC; http://ccmc.gsfc.nasa.gov/) at NASA/GSFC.

## 3. Results and Discussion

### 3.1. Travel Time Error

We compare the travel time of a CME predicted by the WSA-ENLIL model with the observed travel time. The travel time is the difference between the CME-associated shock arrival time at the Earth and the CME start time. Figure 1 shows that the comparison of the travel times between observation and prediction. In the cases of the elliptical and the asymmetric cone models, their arrival times tend to be earlier than those of observations.

We estimate the shock arrival times of 29 halo CMEs at the Earth. The prediction error of the shock arrival time is given by

$$dT_{err} = T_{model} - T_{obs}$$

for each event. The negative error means that the WSA-ENLIL model predicts a shock arrival time earlier than the observed shock arrival time. We make a comparison between the results with three cone models and an empirical model (Kim et al., 2007). In the empirical model, the traveling time in hour can be expressed as $T = 76.86 - 0.02 * V_{CME}$.

Figure 4 shows the histogram of arrival time error for three cases and its bin size is 6 hours. The arrival times of CMEs for the elliptical and asymmetric cone models tend to be earlier than those for the ice-cream cone model. In Table 1, the mean absolute error (MAE) of the arrival times for the asymmetric cone model is 10.3 hours, which is about 1 hour smaller than those of the other models (11.4 h for the elliptical cone model and 11.5 h for the ice-cream cone model). And the root mean square (RMS) errors are approximately 13 hours, which are very similar to one another. It is noted that all three models have a few events having arrival time errors larger than 24 hours. The mean values of the arrival time errors for three cone types are all negative, which implies the overestimation of input radial velocities. The mean radial velocities are 1266 $km/s$, 1183 $km/s$, and 1367 $km/s$ for the elliptical cone model, the ice-cream cone model, and the asymmetric cone model, respectively. These results show that a large negative value of the mean arrival time error for the asymmetric cone model is caused by the overestimated radial velocities.

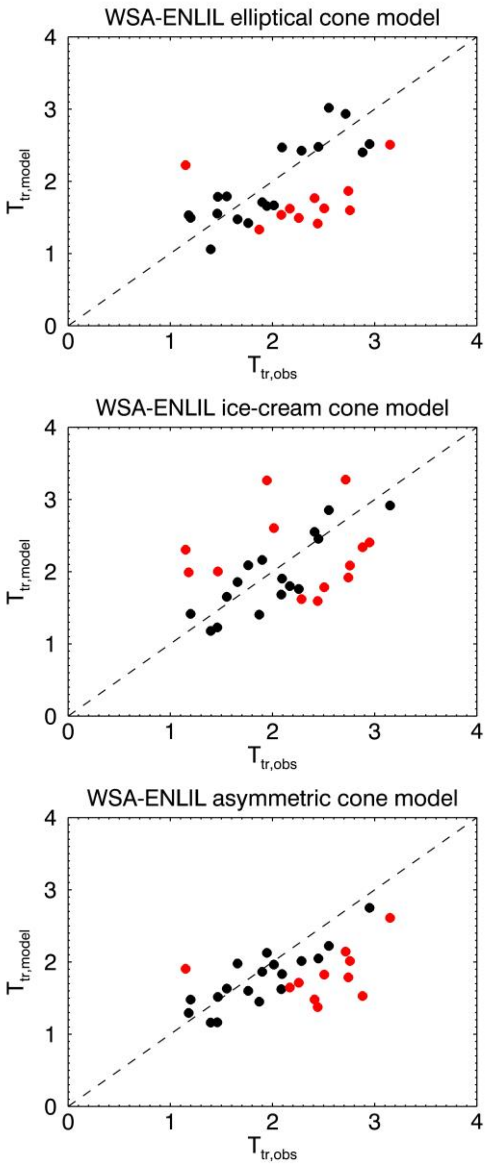


Figure 3. Comparison of the travel times between model results and observations. Red dots represent events whose arrival time errors are larger than 12 hours. Dashed line corresponds to the case that the arrival times of the model are consistent with those of observations.

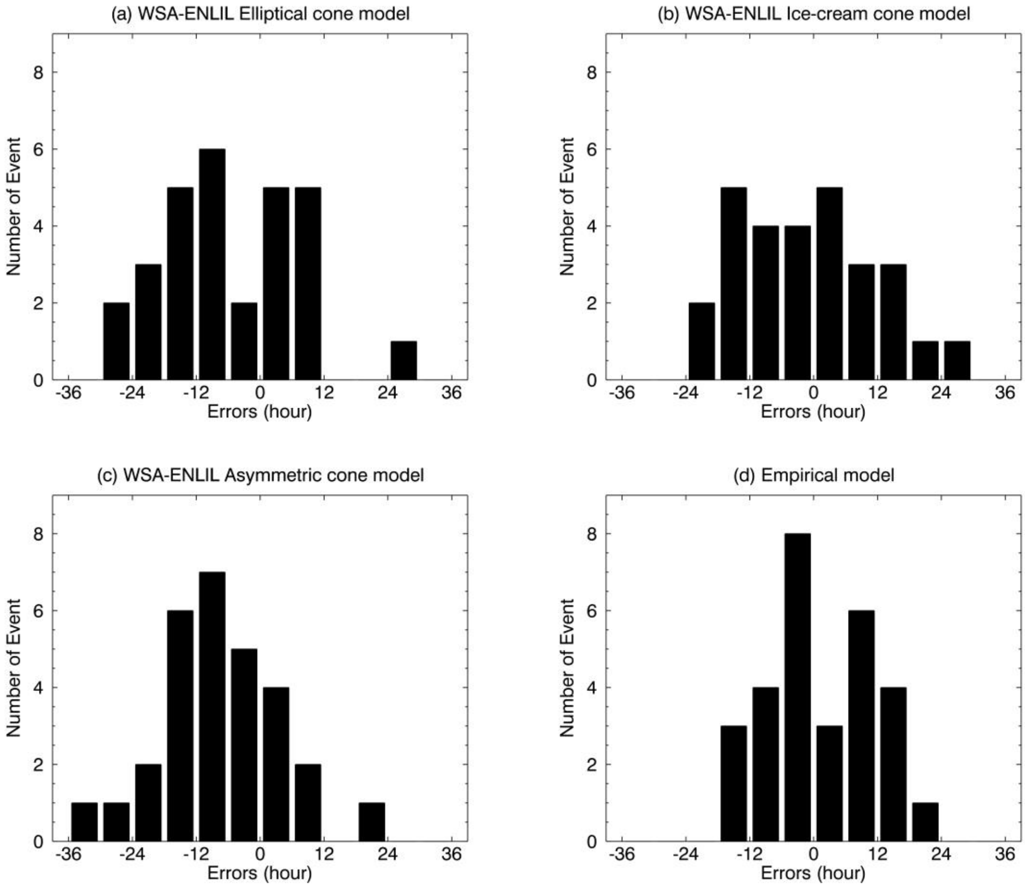


Figure 4. Histogram of arrival time error: (a) the WSA-ENLIL elliptical cone model, (b) the WSA-ENLIL ice-cream cone model, (c) the WSA-ENLIL asymmetric cone model, and (d) the empirical model

| | WSA-ENLIL elliptical cone model | WSA-ENLIL ice-cream cone model | WSA-ENLIL asymmetric cone model | Ensemble WSA-ENLIL model | Empirical model |
|---|---|---|---|---|---|
| MAE | 11.4 | 11.5 | 10.3 | 9.5 | 8.8 |
| RMSE | 13.5 | 13.7 | 13.1 | 11.8 | 10.2 |
| Mean | -5.5 | -0.8 | -7.3 | -4.6 | 1.7 |

Table 1. Mean absolute error (MAE), rout mean square error (RMS error), and Mean of the values plotted in Figure 4 for the WSA-ENLIL model with three cone types and the empirical model.

We compare the arrival time error of the WSA-ENLIL model using three cone types with that of the empirical model. As a result, the MAE of the arrival times for the empirical model is smaller (8.8 hours) than those of the others and all errors are within 24 hours. The MAE of their ensemble average errors for three cone models is 9.5 hours, which is smaller than that of each cone model and still larger than that of the empirical model.

3.2. Speed and Density at 1 AU

We compare the predicted and observed peak values of solar wind parameters (speed and density) near the shock arrival time. We find that these values are approximately similar to each other. In the case of density comparison, the result is different from that of Taktakishvili et al. (2011) who found an approximately 3 times overestimation of the peak density. In the case of the speed, it shows a little overestimation for the elliptical and asymmetric cone models while the ice-cream cone model gives approximate similar values with the observations. Our results are consistent with Taktakashvili et al. (2011) who showed that the model values are not far from the observations.

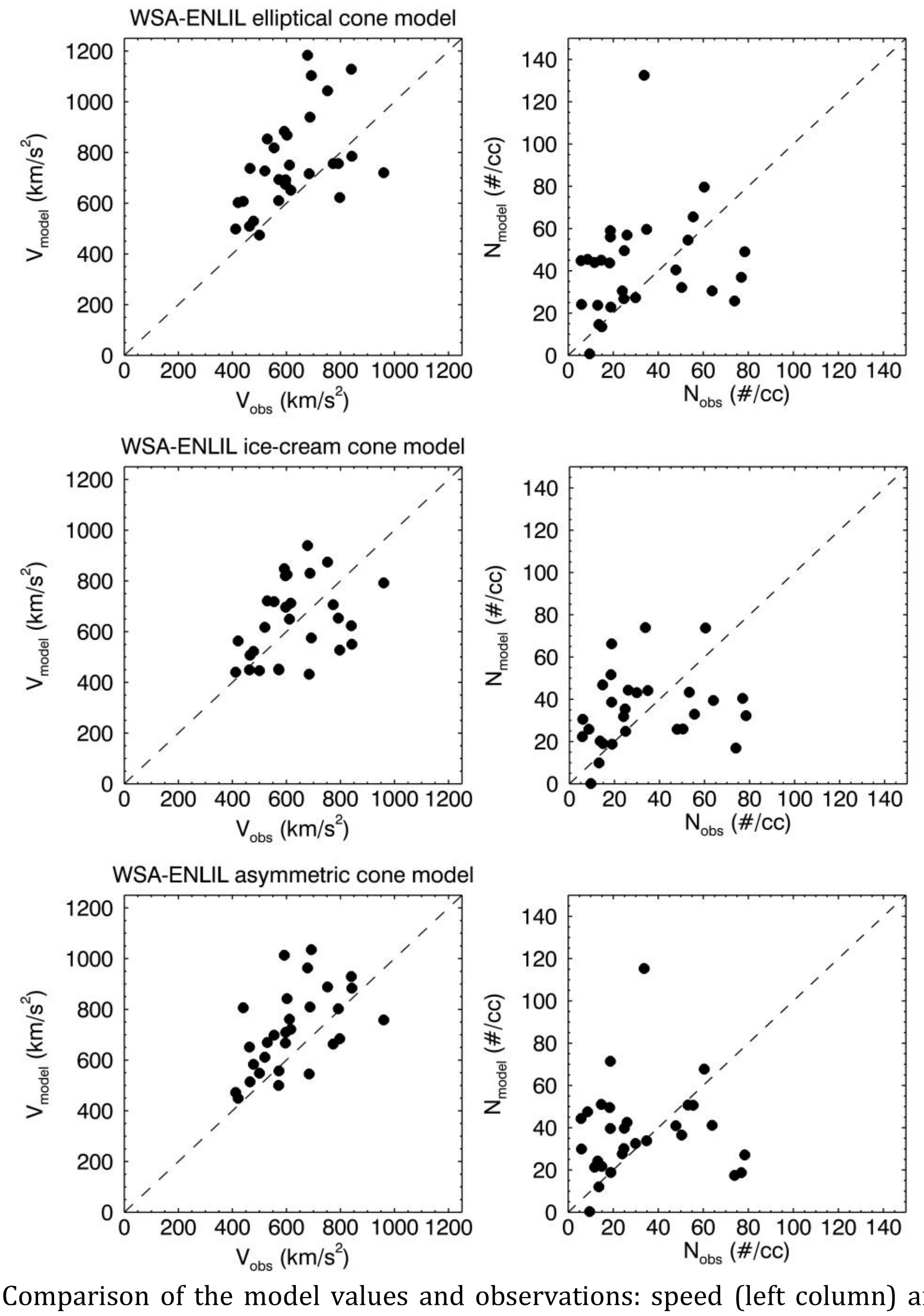


Figure 5. Comparison of the model values and observations: speed (left column) and density (right column) near the CME shock arrival time. Dashed line corresponds to the case that the model values are consistent with those of observations.

## 4. Summary and Future Work

We have examined the performance of the WSA-ENLIL cone model with three cone types using 29 HCMEs from 2001 to 2002. The mean absolute error (MAE) of the arrival times for the asymmetric cone model is 10.6 hours, which is about 1 hour smaller than those of the other models. Their ensemble average of MAE is 9.5 hours. We found that these models predict the arrival times of CMEs at the Earth earlier than those of observations due to the overestimation of the CME initial speeds from cone models. We also compare the predicted and observed peak values of speed and density near the shock arrival times. We find that these values are approximately similar to each other. We are extending the comparison using more events.

We are planning to optimize the input parameters of the WSA-ENLIL model in several aspects. There might be some uncertainties of free parameters such as the initial density ratio between CME and background, and an ambient fast solar wind density and speed. Therefore we are looking for a possibility that the initial density ratio can be determined from coronagraph observations. Furthermore we may need to consider CME-CME interactions in the heliosphere since some CME events during the solar maximum period are sequentially erupted and interacted with each other in the heliosphere.

## 5. References

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